Project: 1163
Project title: C2Phase: Closure of the Cloud Phase
Principal investigator: Corinna Hoose
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Subproject A: Statistical emulation of the aerosol effects on convective precipitation for an Earth System Model

Aerosol-cloud interactions are the most uncertain aspect in global warming, so we want to improve their representation in climate models. In detail we want to include the aerosol effect on precipitation into the convective parameterization of a coarse grid model. For this an idealized perturbed parameter and initial condition ensemble (PPE) representing the different convective regimes that occur in a global model has been built. The single experiments are performed in a Cloud Resolving Model setup of ICON (CRM) using a torus grid with 300 m horizontal resolution, double moment microphysics and 3D turbulence. As initial data, an adapted version of Weisman Klemp profiles is used with highly variable “profile parameters” (such as height and potential temperature of the tropopause, moisture decrease) in order to represent tropical as well as mid-latitude conditions. Nine “base profiles” were created and perturbed based on Latin-Hypercube sampling. The height and amplitude of the warm bubble, which was used to trigger the convection, were also perturbed, as well as the amount of aerosol. Derived “input parameters” (such as CAPE, temperature and relative humidity at different heights) were calculated and compared to global model results to ensure a good fitting to global convective regimes (see Figure 1).

To emulate the results of the PPE, we trained different machine learning architectures from the python module sklearn, including a Random Forest (RF) and a Histogram Gradient Boosting (HGB) model, which are most promising. For the training, we used the derived “input parameters” (see above), since they are also available in a global model run. We tried several variations of training parameters and found that an optimal selection would be a set consisting of: CAPE, CIN, temperature difference between 3km and ground, relative humidity at ground level and in 1 km height and (logarithmic) aerosol quantity (CCN). As shown in Figure 2, it is in principle possible to emulate the amount of precipitation with this set of training parameters.

The prediction of the amount of precipitation and most of the process rates is relatively good, except autoconversion and nucleation. Furthermore, the performance of RF and HGB is comparable, although HGB is slightly better in most cases (lower RMSE, higher R2). The most important information for training is by far CAPE, followed by temperature difference and moisture at ground level. The influence of CIN and CCN is negligible in most cases (compared to the dominant feature importance of CAPE). Since the emulation process is not able to predict the sensitivity to CCN, we now want to train the relative effect of CCN to embed it in the coarse model.

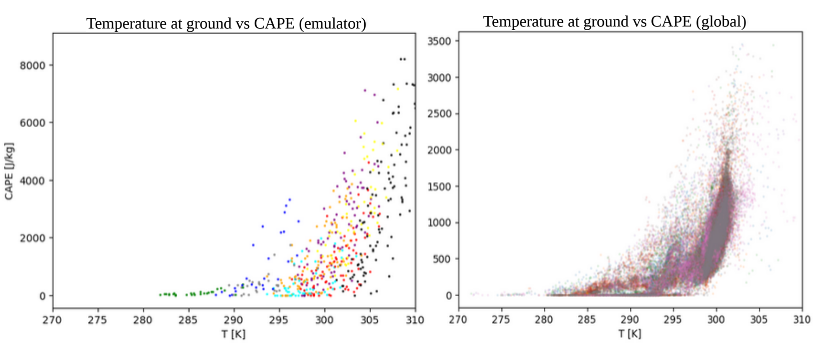

Figure 1: The emulated version of the results of the PPE should be used in an global model setting, thus the distribution of the derived “input parameters” for the PPE should fit to the distribution of the extracted values from global model runs. For the 2 dimensional cut-set of CAPE and temperature at ground this fitting is very good as visible in the comparison of the left and right panel.

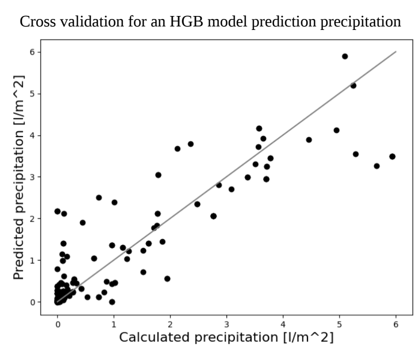

Figure 2: The HGB model was trained 200 times on the entire dataset, excluding each experiment once. Then, for this experiment, the predicted amount of precipitation (given by the HGB model trained on the residual dataset) is compared with the actual amount (given by the CRM). Each point thus corresponds to one trained HGB model.

Subproject B: Evaluating Low-Level Marine Arctic Clouds: Comparing Satellite Observations and DYAMOND Simulations

Climate models struggle to accurately represent the thermodynamic phase of Arctic low-level clouds. To evaluate low-level Arctic clouds, we compared the mean liquid fraction from active satellite measurements (*DARDAR; Ceccaldi et al., 2013, https://doi.org/10.1002/jgrd.50579*) with simulations from several models participating in the DYAMOND project (*Steven et al., 2019, https://doi.org/10.1186/s40645-019-0304-z*). Unlike traditional low-resolution climate models, the DYAMOND models operate at km-scale resolution, providing a better representation of cloud processes.

Observations show that both low and mid-low-level clouds have a higher mean liquid fraction over sea ice than over the open ocean, a feature that most models do not consistently reproduce (Figure 3). Only one model, GEOS, reproduces the observed higher mean liquid fraction over sea ice for low-level clouds. This may be related to the model's interactive two-moment aerosol-cloud microphysics, which allows for a better representation of the cloud's thermodynamic phase. Dietel et al. (*2024, https://doi.org/10.5194/acp-24-7359-2024*) showed that sea salt aerosol concentrations are higher over the open ocean than over sea ice, possibly correlated to a higher concentration of ice nucleating particles. Our results therefore suggest that improving the representation of aerosol–cloud interactions is important for simulating low-level Arctic clouds. We are currently extending the analysis to assess the impact of these model biases on cloud radiative effects at top of the atmosphere and writing up these results for a publication.

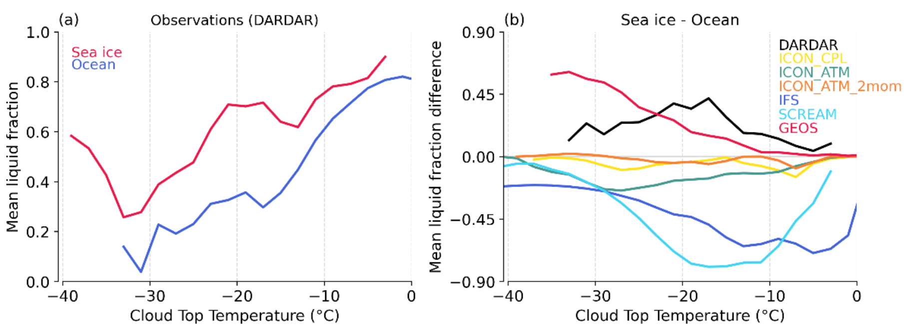

Figure 3: (a) Mean liquid fraction of low-level clouds as a function of cloud top temperature (CTT), calculated for each DARDAR low-level cloud profile over the Arctic region and averaged over 1 °C bins of CTT. Panel (b) shows the mean liquid fraction differences between low-level cloud profiles over sea ice and ocean for DARDAR and DYAMOND model simulations.

Subproject C: Secondary ice processes

In heavily precipitating convective clouds, secondary ice production (SIP) processes are known to significantly influence their microphysical and radiative properties. Here, to assess the impact of SIP on convective clouds, we simulated a mesoscale convective system (MCS) case using ICON with a horizontal resolution of 1.6 km. The SIP processes implemented in ICON include: 1) the Hallett-Mossop rime-splintering process, 2) raindrop freezing and shattering, 3) ice-ice collisions, and 4) sublimation of snow and graupel. The MCS case, characterized by high precipitation (> 5 mm/hr), was observed during the Organized Convection and EarthCARE (*https://www.eorc.jaxa.jp/EARTHCARE/data/L2prd_list_std_e.html*) Studies over the Tropical Atlantic (ORCESTRA, *https://orcestra-campaign.org/orcestra.html*) campaign on September 3, 2024. The results are shown in Figure 4.

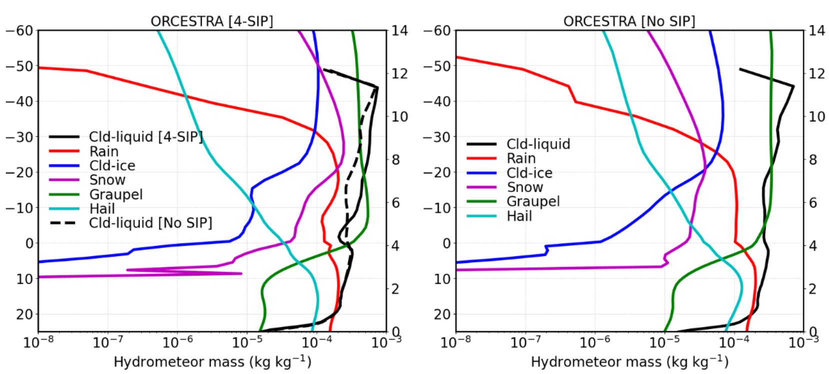

Figure 4: Profiles of the mass mixing ratios of cloud and precipitation hydrometeors, simulated with all four SIP processes (left panel) and without SIP processes (right panel).

The profiles show that when SIP processes are included, the predicted mass of cloud liquid decreases by about 30% in the mixed-phase regions of the simulated ORCESTRA clouds. This reduction is due to the increased growth of additional (secondary) ice fragments from SIP. Similarly, when SIP is included, the rain mass also decreases by the same factor, mainly attributed to the smaller sizes of cloud droplets and raindrops compared to simulations without SIP.

This highlights the critical role of SIP processes in accurately representing clouds and associated precipitation.